

An Explicit Canopy BRDF Model and Inversion

Shunlin Liang and Alan H. Strahler

Boston University

ABSTRACT

Based on a rigorous canopy radiative transfer equation, the multiple scattering radiance is approximated by the asymptotic theory, and the single scattering radiance calculation, which requires an numerical integration due to considering the hotspot effect, is also simplified. A new formulation is presented to obtain more exact angular dependence of the sky radiance distribution. The unscattered solar radiance and single scattering radiance are calculated exactly, and the multiple scattering is approximated by the delta Two-Stream atmospheric radiative transfer model. The numerical algorithms prove that the parametric canopy model is very accurate, especially when the viewing angles are smaller than 55°. Powell algorithm is then used to retrieve biospheric parameters from the ground measured multiangle observations.

INTRODUCTION

Some canopy parametric directional reflectance models have been published based on the radiative transfer theory (Suits, 1972; Verhoef, 1984; Camillo, 1987; Nilson and Kuusk, 1989; Pinty and Verstraete, 1991). However, most of them are based on the Two-Stream approximation or its variants. Our numerical calculation (Liang and Strahler, 1992a) using Gauss-Seidel algorithm has shown that the multiple scattering component is over 50% of the total upwelling radiance in the near-IR region. Therefore further developments of accurate approximation approaches are very necessary. In this study, we derive an approximate solution of the multiple scattering component to a canopy radiative transfer equation based on the asymptotic theory in which the canopy is treated as a dense and vertically finite medium, and the soil reflectance is also incorporated into this formulation.

Most of existing parametric canopy models have not incorporated sky radiance component in a good manner (Ahmad and Deering, 1991, Suits, 1972; Nilson and Kuusk, 1989). Either the canopy is completely decoupled from the atmosphere or downward radiances are treated as isotropic. Most of the existing parametric models of atmospheric radiative transfer are mainly used for flux calculations. A new formulation is presented to improve the accuracy of the angular distribution of the sky radiance.

MODELING CANOPY RADIATIVE TRANSFER

In this study, a more rigorous canopy radiative transfer model has been used as the basis on which the explicit formulae are derived. The details of this model can be found elsewhere (Marshak, 1989; Shultis and Myneni, 1988; Liang and Strahler, 1992a).

The radiation field is decomposed into three parts: uncollided radiance $I^0(\tau, \Omega)$, single scattering radiance $I^1(\tau, \Omega)$ and multiple scattering radiance $I^M(\tau, \Omega)$:

$$I(\tau, \Omega) = I^0(\tau, \Omega) + I^1(\tau, \Omega) + I^M(\tau, \Omega) . \quad (1)$$

For the uncollided solar radiance, the formulae are:

$$I^0(0, \Omega) = \frac{i_0 r_s \mu_0}{\pi} \exp[-\xi(0, \Omega)] , \quad (2)$$

where i_0 (πF_0) is the incident net flux above canopy, and

$$\xi(0, \Omega) = G(\Omega) \frac{\tau_c}{\mu} - \left[\sqrt{\frac{G(\Omega_0)\mu}{G(\Omega)|\mu_0|}} \frac{kH}{\Delta(\Omega_0, \Omega)} \right] t_0 . \quad (3)$$

where t_0 is a transit variable.

For the upwelling single scattering radiance, the approximate formula is:

$$I^1(0, \Omega) = d \exp(b) \left[\frac{1}{a} - \frac{b}{a+c} + \frac{b^2}{2(a+2c)} \right] , \quad (4)$$

where

$$\begin{cases} A_0 = \frac{G(\Omega_0)}{|\mu_0|}, \quad A = \frac{G(\Omega)}{|\mu|}, \quad a = A + A_0, \\ b = \frac{\sqrt{A_0 A} kH}{\Delta(\Omega_0, \Omega)}, \quad c = -\frac{\Delta(\Omega_0, \Omega)}{kH}, \quad d = \frac{\Gamma(\Omega_0, \Omega) i_0}{\pi \mu} . \end{cases} \quad (5)$$

The multiple scattering component is calculated by the asymptotic theory for a finite canopy:

$$I^s(0, \mu) = \frac{\mu_0 F_0}{\pi} \left[R_\infty(\mu, \mu_0) - \frac{mG(A)E(\mu)E(\mu_0)}{\exp(2k\tau_c) - \Gamma G(A)} \right] , \quad (6)$$

where $R_\infty(\mu, \mu_0)$ is the reflectance function of a semi-infinite canopy, $E(\mu)$ is the escape function, $G(A)$ is a transit function, and A^* is the spherical albedo of a semi-infinite medium. All these functions and parameters can be found in the manuscript (Liang and Strahler, 1992b).

The above formula determines the radiance of all levels of scattering. In order to account for the hotspot effect and the dependence of the azimuth angle, the exact single scattering component should be used. Thus the multiple scattering radiance must be subtracted by the approximate single scattering component:

$$I^M(0, \mu) = I^s(0, \mu, \mu_0) - \frac{\omega \mu_0 F_0 p_c(\mu, \mu_0)}{4\pi(\mu + |\mu_0|)} \left[1 - \exp\left(-\frac{\mu + |\mu_0|}{|\mu_0| \mu} \tau_c\right) \right] , \quad (7)$$

where $p_c(\mu, \mu_0)$ is the azimuth-independent part of the Henyey-Greenstein function.

To describe the directional reflectance properties of terrestrial objects, the BRDF is preferred. The total canopy BRDF becomes the sum of the exact single scattering term plus the uncollided sunlight reflectance term and the approximate multiple scattering term:

$$R(\tau_i, \Omega, \Omega_0) = \frac{I^1(0, \Omega) + I^0(0, \Omega) + I^M(0, \Omega)}{\mu_0 F_0} . \quad (8)$$

This work supported by the National Aeronautics and Space Administration under grant NAGW-2082, contract NAS5-30917, and U. S. National Science Foundation under grant INT-9014263.

MODELING DOWNWARD SKY RADIANCE

Since the classic Two-Stream approximation of the atmospheric radiative transfer is mainly used for flux calculations, this method is reliable only for integrated quantities as opposed to angular-dependent radiances. To improve the accuracy of the angular distribution of the sky radiance, the radiation field is divided into three parts, as we did for the canopy: unscattered solar radiance, single scattering radiance, and multiple scattering radiance. We here do not give the corresponding equations and boundary conditions, the interested readers are referred to our previous paper (Liang and Strahler, 1992a). For the first two components, their downward radiances are:

$$\begin{aligned} I_a^0(\Omega) &= |\mu_0| F_{a0} \exp\left(-\frac{\tau_a}{|\mu_0|}\right) \\ I_a^1(\Omega) &= \frac{|\mu_0| F_{a0} \omega_a P(\Psi)}{4(|\mu_0| - |\mu|)} t_1 \quad \mu \neq \mu_0 \\ I_a^1(\Omega) &= \frac{\omega_a F_{a0} \tau_a}{4|\mu_0|} P(\Psi) \exp\left(-\frac{\tau_a}{|\mu_0|}\right) \quad \mu = \mu_0 \end{aligned} \quad (9)$$

where t_1 is a transit variable. For multiple scattering calculation, the Two-Stream approximation is applied. Here we use the hybrid modified Eddington-delta approximation (Meador and Weaver, 1980). In their paper, they gave us the formula only for the black background. Here the formula considering the canopy spherical albedo ρ calculated from the canopy BRDF developed above is:

$$I_a(\mu) = \frac{1}{t_2} \left\{ (1 - g^2) t_3 + g_a^2 \delta(\mu - \mu_0) M^-(\tau_a) \right\}, \quad (10)$$

where t_2 and t_3 are transit variables, defined as

$$\begin{aligned} t_2 &= 1 - g^2(1 - |\mu_0|) \\ t_3 &= (1 + 1.5\mu) M^+(\tau_a) + (1 - 1.5\mu) M^-(\tau_a) \end{aligned}$$

The integrated variables I^+ and I^- are:

$$\begin{cases} I^+(\tau) = X_1 + X_2 + C \exp\left(-\frac{\tau}{\mu_0}\right) \\ I^-(\tau) = \frac{1}{\gamma_2} \left[(\gamma_1 - \eta) X_1 + (\gamma_1 + \eta) X_2 + t_0 \exp\left(-\frac{\tau}{|\mu_0|}\right) \right] \end{cases} \quad (11)$$

and X_1 and X_2 are defined as

$$\begin{aligned} X_1 &= \frac{t_0 w_2 - w_0(\gamma_1 + \eta)}{(\eta + \gamma_1) w_1 + (\eta - \gamma_1) w_2} \exp(\eta \tau) \\ X_2 &= -\frac{t_0 w_1 - w_0(\gamma_1 - \eta)}{(\eta + \gamma_1) w_1 + (\eta - \gamma_1) w_2} \exp(-\eta \tau) \end{aligned} \quad (12)$$

Other parameters are given in the manuscript (Liang and Strahler, 1992b). The multiple scattering downward radiance is the total approximate radiance abstracted by approximate single scattering radiance

$$I_a^M(\mu) = I_a(\mu) - I_a^1(\mu), \quad (13)$$

where the calculation of $I_a^1(\mu)$ follows the same formulae as those of $I_a(\mu)$ except that g_a and ρ are set to zeroes when calculating I^+ and I^- . Thus the total sky downward radiance is the sum of three components:

$$I_a(\Omega) = I_a^0(\Omega) + I_a^1(\Omega) + I_a^M(\mu) \quad (14)$$

It is possible to incorporate a δ -function adjustment to account for the forward scattering peak in the context of Two-Stream approximation. More details are omitted here.

MODEL VALIDATION

To evaluate the accuracy and analyze the behavior of the parametric BRDF model of the leaf canopy, Monte-Carlo methods (Antyufeev and Marshak, 1990; and Ross and Marshak, 1988) are used to test the accuracy of the present model. Fig. 1 presents the comparison of the bidirectional reflectance of three approaches for the erectophile canopy (mainly vertical leaves). Two sets of curves correspond to two solar zenith angles $\theta_0 = 60^\circ$ and $\theta_0 = 30^\circ$. The solid lines stand for our present model, dotted lines for the Antyufeev-Marshak model, and dashed lines for the Ross-Marshak model. There is a good agreement among these three models. However, the directional reflectance in our model is greater than others when the solar zenith angle is 30° .

Fig. 2 illustrates another comparison of the present model with the Antyufeev-Marshak model for the planophile canopy (mainly horizontal leaves). Solid lines for our model have larger values when the viewing angles are greater than 55° , especially when the solar zenith angle is 60° . A series of other experiments using Gauss-Seidel algorithm also verifies that the present parametric model cannot well predict the reflectance when the viewing angles are greater than $55^\circ - 60^\circ$. The corresponding parameters can be found in the literature mentioned previously. The numerical algorithms usually require several hours to get good results, but our parametric model only needs decades of second in the SPARC-2 workstation.

The parametric sky radiance distribution model is validated using the DISORT numerical code based on the discrete-ordinate algorithm (Stamnes et al., 1988). Fig. 3 illustrated the comparison of the present parametric model with the numerical model for the aerosol scattering above a Lambertian surface. It can be found that if the aerosol optical depth is smaller than 2.0, our parametric model is quite accurate, especially when the zenith angle is smaller than 75° . If the sky is clear, the aerosol optical depth is usually smaller than 0.2 in the near-IR bands. Although one set of results is presented, other comparisons can draw the same conclusion.

INVERSION ALGORITHM AND DATA ANALYSIS

Having created the canopy BRDF model and the sky radiance distribution model, the remaining issue is how to estimate parameters in these models from measured directional data. Like ordinary inversion studies (Goel, 1988), The optimum technique is used to invert them through minimizing the merit function consisting of the sum of squares of residual and the penalty function:

$$F = \sum_{k=1}^K w_k [I_k - \hat{I}_k(\Psi_A, \Psi_B)]^2 + f(\Psi_A, \Psi_B) \quad (15)$$

where w_k is the weight factor, I_k is the measured radiance, $\hat{I}_k(\Psi_A, \Psi_B)$ is the predicted radiance by models with canopy BRDF parameters Ψ_A and atmosphere parameters Ψ_B , and $f(\Psi_A, \Psi_B)$ is the penalty function which keeps estimated parameters or their functions in reasonable regions.

The construction of the penalty function follows the Siddall algorithm (Siddall, 1972) and Powell algorithm (Powell, 1964) is used to retrieve interested parameters from Soybean data (band four) measured by Ranson et al (1984) on 17 August 1980. Only four variables are retrieved, and other parameters are set to measured values or estimated values. The inversion results are reported in Table I. It seems that LAI is very accurately inverted, but LAD

is not so accurate. More discussions are presented in our manuscript(1992b).

REFERENCES

- S. P. Ahmad and D.W. Deering, "A simple analytic function for bidirectional reflectance," *J. Geophys. Res.*, in press.
- V. S. Antyufeyev, and A. L. Marshak, "Monte Carlo method and transport equation in plant canopies," *Remote Sens. Environ.*, vol.31, pp. 183-191, 1990.
- P. Camillo, "A canopy reflectance model based on an analytical solution to the multiple scattering equation," *Remote Sens. Environ.*, vol. 23, pp. 453-477, 1987.
- N. S. Goel, "Models of vegetation canopy reflectance and their use in estimation of biophysical parameters from reflectance data," *Remote Sens. Rev.*, vol. 4, pp. 1-222, 1988.
- S. Liang and A. H. Strahler, "Calculation of the angular radiance distribution for a coupled system of a atmosphere and canopy media using an improved Gauss-Seidel algorithm," submitted to *IEEE Trans. Geosci. Remote Sens.*, 1992a.
- S. Liang and A. H. Strahler, "A parametric BRDF model of the canopy radiative transfer and inversion," in prep., 1992b.
- A. L. Marshak, "The effect of the hot spot on the transport equation in plant canopies," *J. Quant. Spectrosc. Radiat. Transfer*, vol. 42, pp. 615-630, 1989.
- W. E. Meador and W. R. Weaver, "Two-stream approximations to radiative transfer in planetary atmospheres: A unified description of existing methods and a new improvement," *J. Atmos. Sci.*, vol. 37, pp. 630-643, 1980.
- T. Nilson and A. Kuusk, "A reflectance model for the homogeneous plant canopy and its inversion," *Remote Sens. Environ.*, vol 27, 157-167, 1989.
- B. Pinty and M. M. Verstraete, "Extracting information on surface properties from bidirectional reflectance measurements," *J. Geophys. Res.*, vol. 96, pp. 2865-2874, 1991.
- M. J. D. Powell, "An efficient methods for finding the minimum of a function of several variables without calculating derivatives," *Computer J.*, vol. 7, pp. 155-162, 1964.
- K. J. Ranson, L. L. Biehl, and C. S. T. Daughtry, "Soybean Canopy Reflectance Modeling Data Sets," *LARS Technical Report 071584*, pp. 1-46, 1984.
- J. K. Ross, and A. L. Marshak, "Calculation of canopy bidirectional reflectance using the Monte Carlo method," *Remote Sens. Environ.*, vol. 24, pp. 213-225, 1988.
- J. K. Shultis and R. B. Myneni, "Radiative transfer in vegetation canopies with an isotropic scattering," *J. Quant. Spectrosc. Radiat. Transfer*, vol. 39, pp. 115-129, 1988.
- J. N. Siddall, *Analytical Decision-making in Engineering Design*, Prentice-Hall, Englewood, Cliffs, NJ., 1972
- K. Stamnes, S. C. Tsay, W. Wiscombe, and K. Jayaweera, "Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media," *Appl. Opt.*, vol. 27, pp. 2502-2508, 1988.
- G. W. Suits, "The calculation of the directional reflectance of a vegetative canopy," *Remote Sens. Environ.*, vol 2, pp. 117-125, 1972.
- W. Verhoef, "Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model," *Remote Sens. Environ.*, vol. 16, pp. 125-141, 1984.

Fig.1 validation for the erectophile canopy

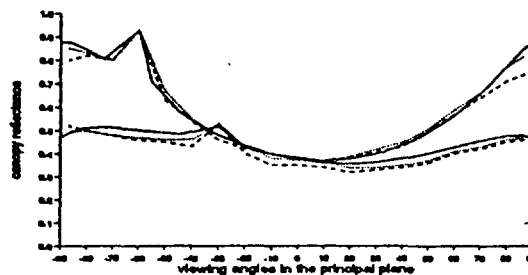


Fig.2 Validation for the planophile canopy

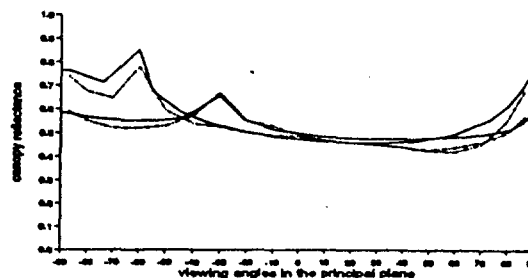


Fig.3 Validation of the sky radiance model

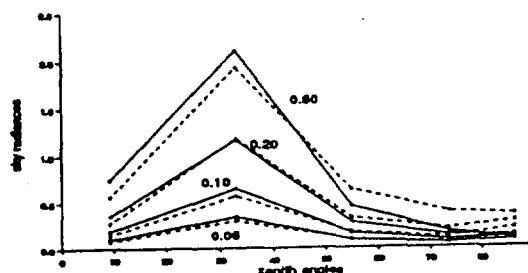


TABLE I

INVERSION RESULTS FOR THE SOYBEAN DATA

Data set #	θ_s	θ_v	Retrieved values			
			LAI	u	v	ϵ_r
c1	38	136	2.831	2.786	2.767	0.172
c2	35	145	2.851	2.796	3.846	0.168
c3	32	163	2.856	3.950	8.674	0.174
c4	31	174	2.867	5.050	10.001	0.164
c5	31	196	3.024	3.013	8.227	0.162
c6	33	206	3.086	3.067	8.845	0.149
c7	36	217	2.877	2.721	5.011	0.156
c8	38	225	3.041	3.504	9.825	0.155
c9	44	237	2.971	3.907	8.309	0.164
c10	42	243	3.090	3.757	8.210	0.172
c11	55	251	2.893	2.922	3.875	0.183
c12	61	258	2.895	2.078	2.839	0.193
measured value			2.90	1.806	2.447	